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# Transmission Characteristics of Suspension Seats in Multi-Axis Vibration Environments


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**Human Effectiveness Directorate**
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# Transmission characteristics of suspension seats in multi-axis vibration environments

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**Abstract**

The multi-axis vibration transmission characteristics of selected suspension seats were investigated in the laboratory. Subjects were exposed to a flat acceleration spectrum and two low frequency signals extracted from multi-axis acceleration data recorded at the floor of a passenger locomotive. Triaxial accelerations were measured at the floor of the vibration table and at the interfaces between the subject and mounted seat (seat pan and seat back). The transmission ratios between the overall seat pan and seat back accelerations and floor accelerations provided an effective tool for evaluating the effects of measurement site, vibration direction, and posture among the selected seating systems. The results showed that the system transfer matrix, estimated using a multiple-input/single-output model, would be less than ideal for predicting low frequency operational seat vibration when using suspension seats. The Seat Effective Amplitude Transmissibility (SEAT), estimated for the tested locomotive seats, was used to predict the weighted seat pan accelerations and Vibration Total Values for assessing a 1-h operational exposure in accordance with ISO 2631-1: 1997.

**Relevance to industry**

Multi-axis SEAT values can be estimated for seating systems tested in the laboratory using representative operational exposures. These values can be applied to monitored vehicle floor accelerations to target potentially harmful vibration in accordance with ISO 2631-1: 1997, assuming the operational exposures have similar frequency and magnitude characteristics. The transmission at the seat back should be considered when substantial low frequency multi-axis vibration is present.
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*Keywords:* Suspension seats; Whole-body vibration; Transmissibility; Multi-axis vibration; Comfort; Health

## 1. Introduction

Numerous human vibration studies conducted over the past several decades have shown that the human body is sensitive to low frequency vibration occurring below 10 Hz (Griffin, 1990). Although posture and poor seating have been associated with discomfort and back pain, prolonged exposure to occupational vibration has been considered a contributing factor in the generation of these symptoms in both civilian and military operations (ISO, 1997). Passive, low frequency suspension seats are being used to minimize this vibration, particularly in heavy commercial and off-road vehicles. In general, the passive, low frequency suspension system consists of a low-stiffness spring and damper structure, designed to attenuate vehicle vibration in the frequency range where the major human body resonance occurs in the vertical direction (4–8 Hz). As a consequence, the suspension seat amplifies both fore-and-aft and vertical vibration below 3 Hz (Corbridge, 1987; Smith, 1997). Locomotive engineers in passenger trains are using suspension seats similar to the passive, low frequency design concept described above.

At the request of the Federal Rail Administration's (FRA) Office of Research and Development, the Department of Transportation (DOT) Volpe National Transportation Systems Center collected floor and seat frame triaxial accelerations on selected passenger train locomotives.

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The purpose of collecting the data was to assess the effects of vibration exposure on the engineers. The ISO 2631-1: 1997 provides guidelines for measuring vibration that affects the human body and recommends that the acceleration be measured in all three translational axes at the interfaces between the occupant and contact surfaces (seat pan, seat back, and feet). It was not clear to what extent the measurements taken at the floor of the locomotive reflected the vibration entering the occupant. The vibration at the interface between the human and seat can be estimated from the floor vibration via the transmission characteristics of the coupled human/seat system. In collaboration with DOT, the US Air Force Research Laboratory, Human Effectiveness Directorate (AFRL/RH) conducted a study to evaluate the transmission characteristics of selected suspension seats during exposure to low frequency vibration. The system transfer matrix and transmission ratios were used to investigate the effects of the seating system, measurement site, vibration direction, and posture on the coupling behavior of the occupant/seat system. Using exposures extracted from the DOT locomotive data, health and comfort assessments were conducted in accordance with the guidelines of ISO 2631-1: 1997. The results of this study were used to develop a scheme for targeting potentially harmful vibration exposures transmitted to the occupant based on monitored floor accelerations.

## 2. Methods and materials

### 2.1. Experimental setup and data collection

The study was approved by the Institutional Review Board (IRB) at Wright-Patterson AFB, OH. Subjects were members of the Impact Acceleration Panel at Wright-Patterson AFB, OH. Seven subjects participated in the study, including three females and four males. Body weights ranged from 53 to 97 kg. Four seating configurations were evaluated in this study. Three of the configurations used locomotive seats (United States Seating Company, USSC). Two of these seats were suspension seats (USSC 9002), one of which represented a good-suspension (GS) configuration and the other a bad-suspension (BS) configuration. The suspension seats included a passive spring-damper mechanism configured as a dual shock pendulum scissor system. The hydraulic shock absorbers were mounted between the scissor structure on each side of the seat and the seat frame. Rubber bumpers or end-stops were located to limit the downward motion of the scissor mechanism. In the BS configuration, the hydraulic shock absorbers were removed but the springs and bumpers were not. The third seat was a freight seat (FS) without any suspension mechanism (USSC 9012). Both the suspension seats and FS cushions were cloth-covered. The fourth seat was a rigid metal seat (RS) available in-house. The seat back angle for the locomotive seats was adjusted to six degrees to coincide with the seat back angle of the rigid seat.

The seat heights were adjusted so that the subjects' feet just contacted the floor. The adjustments resulted in slight contact between the bumper and suspension mechanism for at least one subject with the GS seat (one female) (seat heights not recorded for three subjects) and five of the seven subjects for the BS seat (three females and two males). For two of the subjects, the FS could not be adjusted low enough to provide full foot contact with the floor. For both subjects, the heels were raised but the balls of the feet contacted the floor.

Two seating postures were tested in this study. For the back-on posture, subjects were instructed to sit upright with their back in contact with the seat back. For the back-off posture, subjects were instructed to sit upright but lean slightly forward so as not to contact the seat back. The subjects were loosely restrained with a lap belt. During testing, subjects were instructed to place their hands in their laps.

All tests were conducted in the Six Degree-of-Freedom Motion Simulator (SIXMODE) located at AFRL/RH. Each locomotive seat was rigidly mounted onto the vibration table as illustrated in Fig. 1. Triaxial accelerometer packs were used to collect acceleration data in the three orthogonal axes (fore-and-aft ($X$), lateral ($Y$), and vertical ($Z$)). The packs were comprised of miniature accelerometers (Entran EGAX-25, Entran Devices, Inc., Fairfield, NJ) arranged orthogonally and embedded in a Delrin cylinder measuring 1.9 cm in diameter and 0.86 cm in thickness. One pack was secured to the floor beneath the seat (input). Acceleration pads, each containing a triaxial

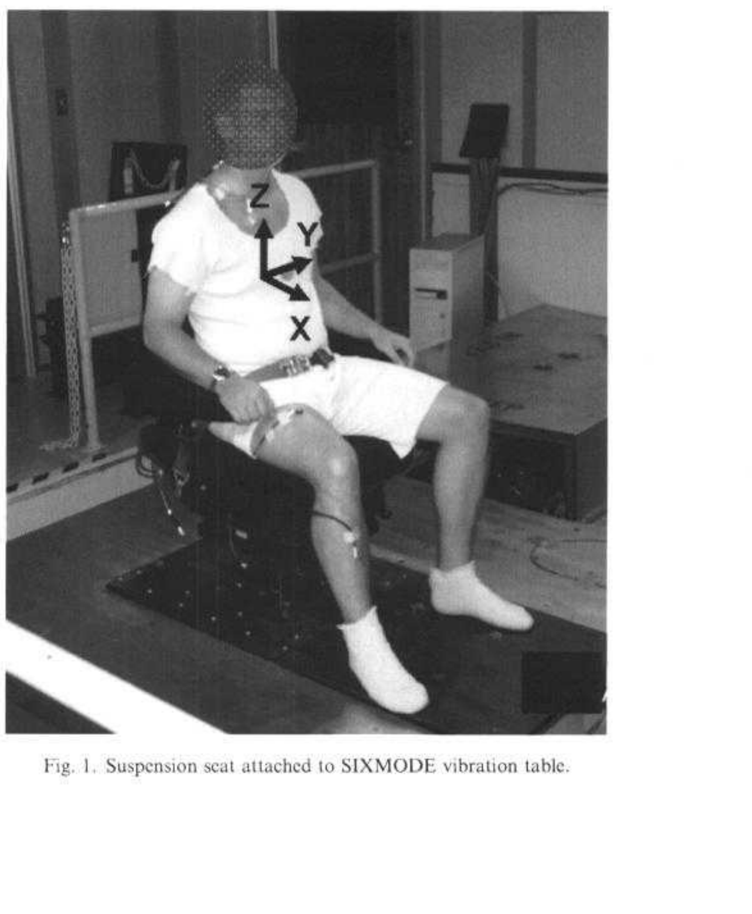


Fig. 1. Suspension seat attached to SIXMODE vibration table.

accelerometer pack, were used to measure triaxial accelerations at the interfaces between the seat and occupant. Each pad consisted of a thin rubber disk measuring approximately 20 cm in diameter. One pad was attached using double-sided tape to the center surface of the seat pan cushion. A second pad was attached using double-side tape to the surface of the seat back cushion, approximately one-third the seat back distance from the seat pan cushion, in the vicinity of the lumbar–thoracic spine transition to insure full contact with the occupant's back. Accelerations were also measured at the manubrium of the chest and at the head using a bite bar. The chest and head results are described elsewhere (Smith et al., 2006).

Three exposure signals were used in the study, including a multi-axis flat acceleration spectrum (FLAT) and two multi-axis signals extracted from the DOT data recorded at the floor of a passenger train locomotive (Signal 1 and Signal 2). The 10-s FLAT signal was computer-generated simultaneously in the three orthogonal directions at 1024 samples/s between 1 and 80 Hz with an overall acceleration level of $1.0\,\mathrm{m\,s^{-2}}$ rms. The 10-s locomotive signals were selected to represent the higher levels of vibration experienced by the engineers. The data were resampled at 1024 samples/s (MATLAB® (The Mathworks, Inc., Natick, MA)) in the three orthogonal directions for simultaneous regeneration in the SIXMODE using an iterative process that minimized the error between the original (desired) signal and table vibration. All three multi-axis signals were repeated to provide 20-s exposures.

Each test session included all testing for a selected seat configuration at both postures and for all three exposure signals. Accelerations were simultaneously collected for 10 s, filtered at 100 Hz (antialiasing), and digitized at 1024 samples/s. The auto- and cross-spectral densities were calculated using Welch's Method (1967) and Matlab®. The acceleration signals were divided into 2-s segments with 50% overlap, providing a frequency resolution of 0.5 Hz. A Hamming window was applied to these segments and the resultant power spectra averaged.

### 2.2. System transfer matrix

Since the locomotive vibration exposures included accelerations in all three translational axes ($X$, $Y$, and $Z$), a multiple-input/single-output model was used to estimate the linear contribution of each axis of floor vibration to each of the output axes (seat pan and seat back) via the system transfer matrix (Bendat and Piersol, 1993; Newland, 1984; Naidu, 1996). For the case where all three input directions ($x$, $y$, and $z$) may contribute to the output $Z$, the system transfer matrix is defined as ($\omega$ has been omitted for simplification) (Newland, 1984):

$$\begin{bmatrix} P_{xZ} \\ P_{yZ} \\ P_{zZ} \end{bmatrix} = \begin{bmatrix} P_{xx} & P_{xy} & P_{xz} \\ P_{yx} & P_{yy} & P_{yz} \\ P_{zx} & P_{zy} & P_{zz} \end{bmatrix} \begin{bmatrix} H_1 \\ H_2 \\ H_3 \end{bmatrix}. \quad (1)$$

Similar equations can be written for the cross-spectra for outputs $X$ ($P_{xX}$, $P_{yX}$, $P_{zX}$), and $Y$ ($P_{xY}$, $P_{yY}$, $P_{zY}$), for a total of nine equations and nine transfer functions. Partial and multiple coherences were also calculated (Naidu, 1996). There is a partial coherence associated with each transfer function, $H$. The partial coherence reflects the extent to which the particular input linearly contributes to the output after removing the effects of the other known inputs. Partial coherences less than unity indicate the presence of other factors (noise). The multiple coherence reflects the extent to which all known inputs linearly contribute to the output. If the output is completely accounted for by a linear response to the known inputs, the result will be unity (Newland, 1984).

### 2.3. Transmission ratio

The root-mean-square (rms) acceleration spectra in the fore-and-aft ($X$), lateral ($Y$), and vertical ($Z$) directions (relative to the seated occupant) at each measurement site were calculated from the power spectra using the frequency resolution of 0.5 Hz. The overall rms acceleration levels ($a_{\mathrm{rms}}$) were calculated in each direction using each frequency component, $i$ as

$$a_{\mathrm{rms}} = \left[\sum_i a^2_{\mathrm{rms}i}\right]^{1/2}. \quad (2)$$

The transmission ratio was calculated as the ratio between the overall seat acceleration and overall floor acceleration in each direction. This ratio is similar to the Seat Effective Amplitude Transmissibility (SEAT) defined in Griffin (1990) and ISO 10326-1: 1992 but does not include weighting of the input and output acceleration spectra (see below). The Repeated Measures Analysis of Variance and Bonferroni test were used to evaluate the significance of seating configuration and posture on the transmission ratios ($P<0.05$).

### 2.4. Weighted accelerations and Vibration Total Values (VTVs)

The acceleration time histories were also analyzed in one-third octave proportional frequency bands using a modified MATLAB® software program developed by Couvreur (1997). These data were used to calculate the weighted accelerations at the seat pan and seat back for assessing comfort and health in accordance with ISO 2631-1: 1997. The weighted seat pan and seat back accelerations in each direction were calculated as

$$a_{\mathrm{wrms}i} = [w_{ji} a_{\mathrm{rms}i}], \quad (3)$$

where $i$ represents the center frequency component and $j$ represents the particular frequency weighting depending on the measurement site (seat pan or seat back) and direction. The overall weighted rms acceleration in each direction was calculated in accordance with Eq. (2) (using weighted

values.) For assessing health, the overall weighted seat pan accelerations were multiplied by the respective multiplying factor, $k$, where $k_x = 1.4$, $k_y = 1.4$, and $k_z = 1.0$ (ISO 2631-1: 1997. For assessing comfort, the point Vibration Total Value (pVTV) was calculated at the seat pan and seat back as

$$\mathrm{pVTV} = \sqrt{k_x^2 a_{wx}^2 + k_y^2 a_{wy}^2 + k_z^2 a_{wz}^2}, \tag{4}$$

where $k$ is the multiplying factor associated with a particular measurement site and direction (ISO, 1997), and $a_{wx}$, $a_{wy}$, and $a_{wz}$ are the weighted overall rms acceleration levels at each respective site in each respective axis. In accordance with ISO 2631-1: 1997, when comfort may be affected by vibration at more than one contact point such as the seat back, it is recommended to calculate the overall Vibration Total Value as the vector sum of the seat pan pVTV and seat back pVTV. In this case, the multiplying factors are defined as $k_x = k_y = k_z = 1.0$ at the seat pan, and $k_x = 0.8$, $k_y = 0.5$, and $k_z = 0.4$ at the seat back. If the seat back vibration cannot be measured, the ISO 2631-1: 1997 recommends that a multiplying factor of $k_x = k_y = 1.4$ be used to calculate the pVTV at the seat (with the back-on posture).

### 2.5. *Seat Effective Amplitude Transmissibility (SEAT)*

The SEAT is used to compare the discomfort associated with a seating system to that associated with sitting on the floor. It can be used to assess the effective vibration isolation of the seating system. The SEAT is calculated as the ratio between the weighted seat pan and weighted floor accelerations:

$$\mathrm{SEAT}_i = \frac{a_{\mathrm{wrms}i}(\mathrm{seat})}{a_{\mathrm{wrms}i}(\mathrm{floor})}, \tag{5}$$

where $a_{\mathrm{wrms}i}$ (seat) is the weighted seat pan vibration in a given direction $i$, $a_{\mathrm{wrms}i}$ (floor) is the weighted floor vibration in the same direction $i$, with $i = X$, $Y$, or $Z$. Eq (5) can also be written as

$$\mathrm{SEAT}_i = \frac{a_{\mathrm{wS}i}}{a_{\mathrm{wP}i}}, \tag{6}$$

in accordance with ISO 10326-1: 1992.

## 3. Results

Fig. 2 illustrates sample acceleration spectra for Signal 2. The figure includes the drive signal extracted from the original locomotive data and the recreated signal measured on the floor of the vibration platform. The floor spectra were highly repeatable among the subjects. Although the input signals were processed between 1 and 80 Hz, the vibration was concentrated in the frequency range below 10 Hz. Both signals showed notable acceleration peaks around 1.5–2.0 Hz, particularly in the $X$ and $Z$ directions. None of the accelerations measured at the seat showed evidence of motions that could be categorized as substantial shock impact where the sudden change in acceleration is short relative to the fundamental frequencies of concern (1.5–2.0 Hz) as defined in ISO 2041: 1990, regardless of the seating height. None of the subjects reported any severe bottoming out of the seat or substantial impact. However, closer inspection revealed that the rubber bumpers or end-stops had been contacted to some extent, particularly on the BS seat.

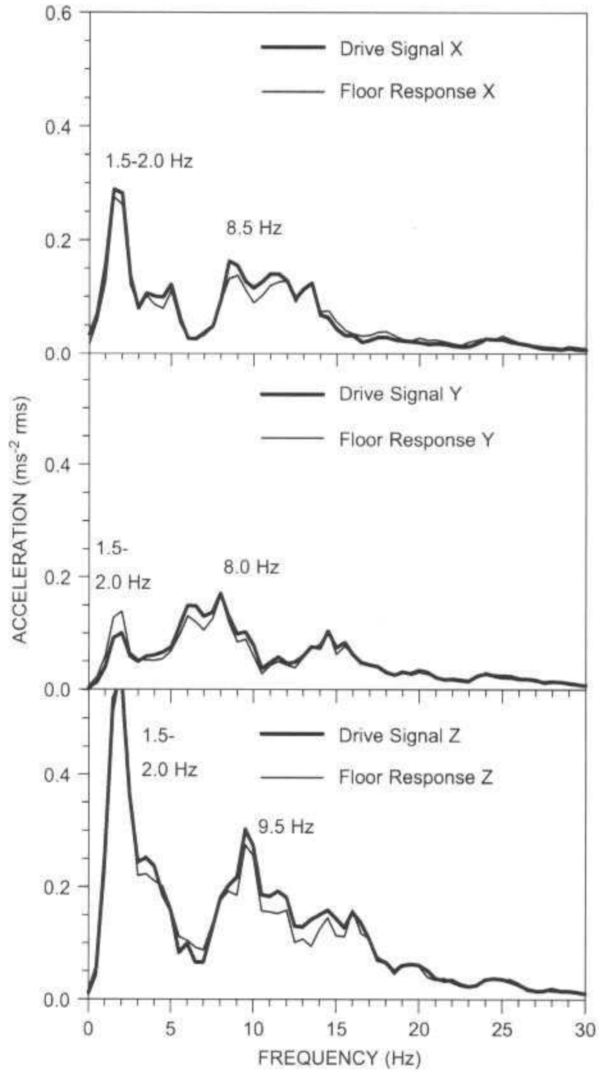


Fig. 2. Locomotive vibration acceleration spectra (Signal 2).

### 3.1. *System transfer matrix (transmissibilities)*

Figs. 3 and 4 illustrate the seat pan and seat back transmissibilities and partial coherences between 1 and 10 Hz for two females and two males (weight range = 53–97 kg) exposed to the FLAT signal using the GS seat and BS seat, respectively. The figures show the transmissibilities between the input and output occurring

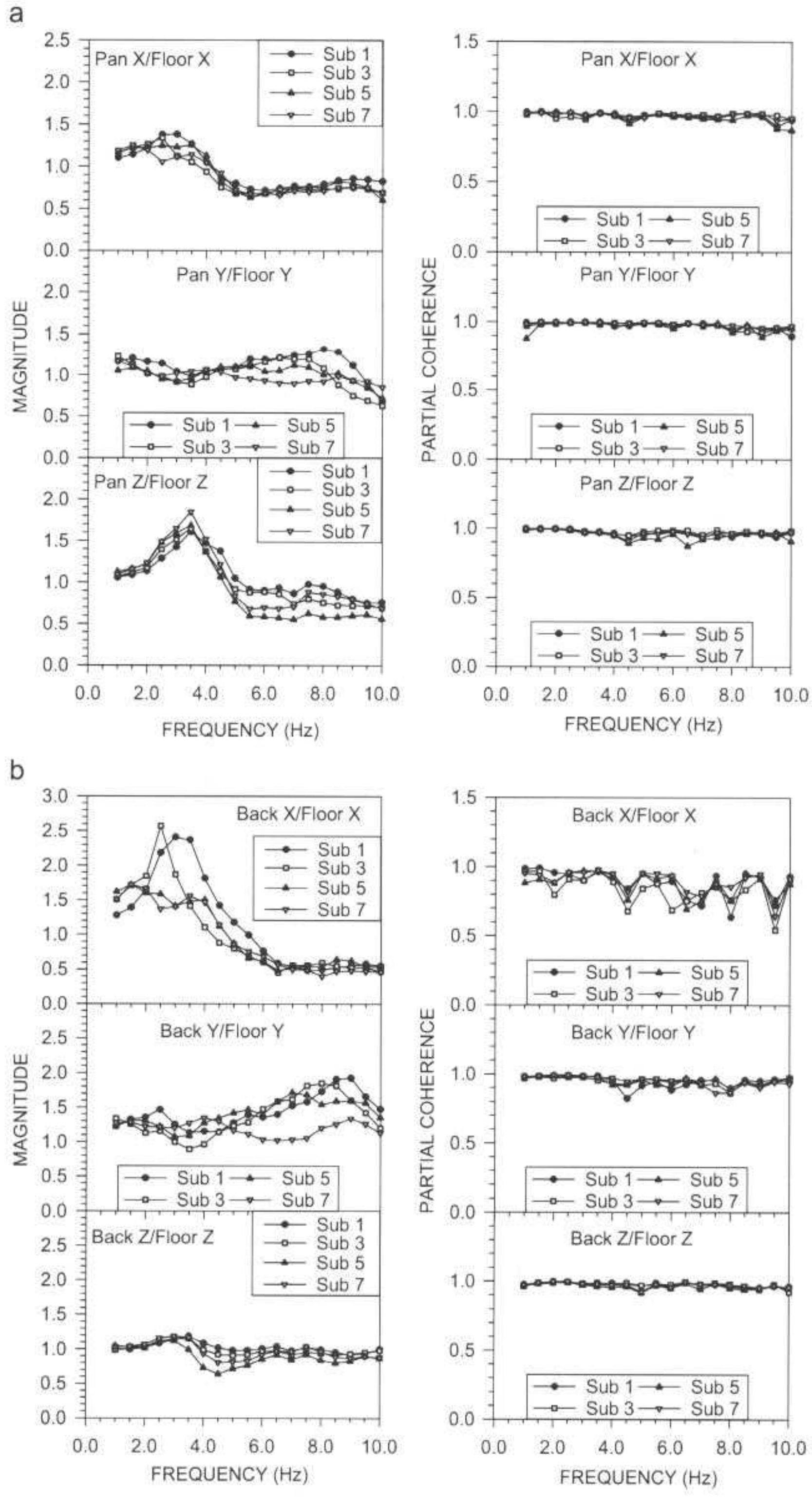


Fig. 3. Seat transmissibilities and partial coherences for FLAT exposure, GS seat (back-on) (a) seat pan, (b) seat back. (Subject 1 = female, 53.6 kg; subject 3 = female, 94.0 kg, subject 5 = male, 75.6 kg, subject 7 = male, 96.5 kg.)

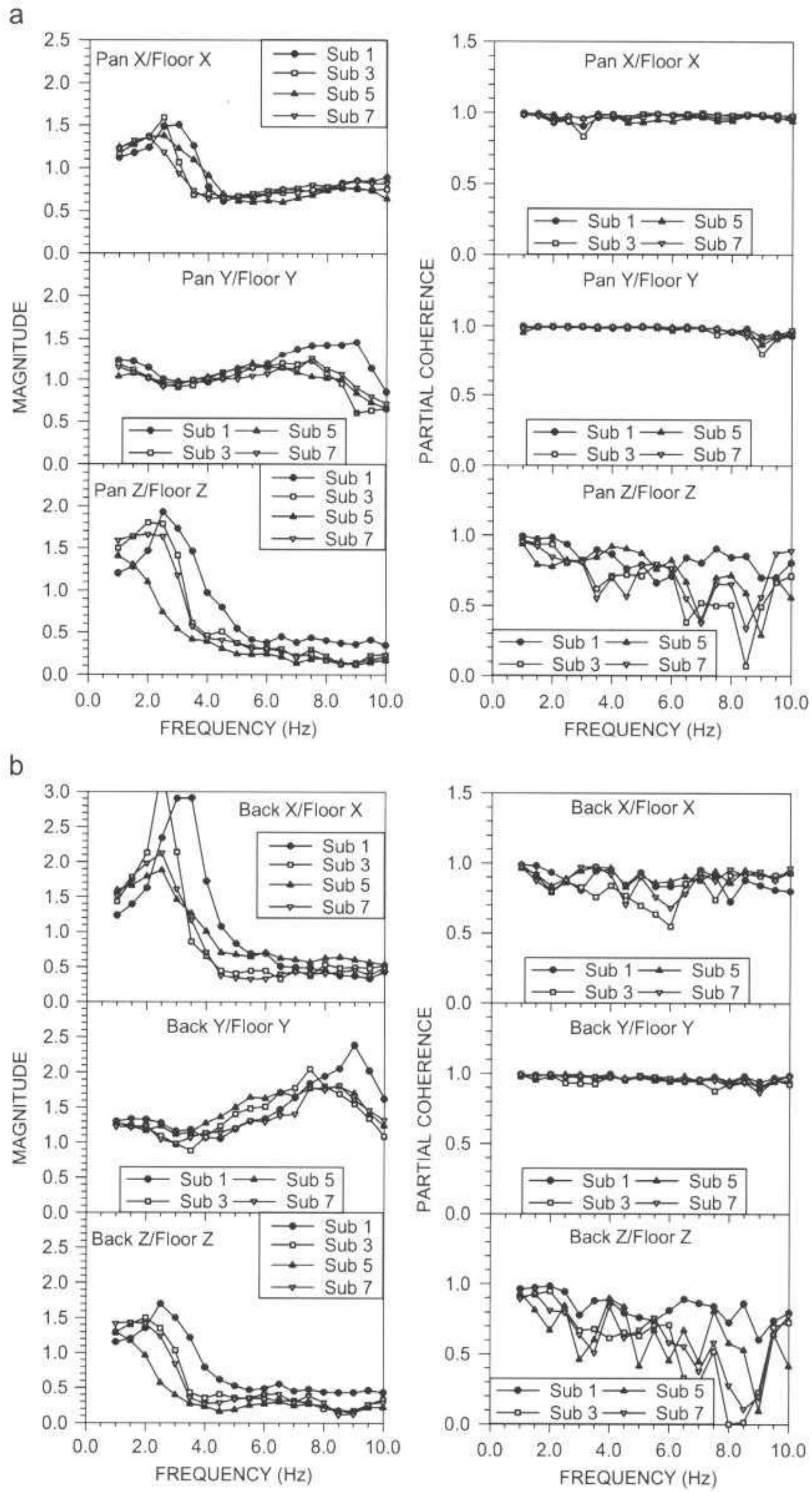


Fig. 4. Seat transmissibilities and partial coherences for FLAT exposure, BS seat (back-on) (a) seat pan, (b) seat back. (Subject 1 = female, 53.6 kg; subject 3 = female, 94.0 kg, subject 5 = male, 75.6 kg, subject 7 = male, 96.5 kg.)

in the same direction. Off-axis contributions were minimal at the seat pan and seat back regardless of the seat configuration. All major peaks occurred between 2 and 4 Hz. The highest seat pan peaks occurred in the $Z$ direction. The highest seat back peaks occurred in the X direction. As illustrated in Figs. 3b and 4b, variations were observed in the seat back peaks in the $X$ direction among the subjects. The partial coherences were high between 1 and 10 Hz (>0.9), but were more variable for the BS seat at non-peak locations in the $X$ and $Z$ directions (Fig. 4b). There was a tendency for the highest seat back transmissibility to occur with two of the three females. The magnitude of the peak did not appear to be related to the body weight since female Sub 1 had the lowest weight and female Sub 3 had the second highest weight among the subjects. Although not shown, the multiple coherences were also high. These results indicated that, for exposures to the FLAT spectrum, the seat responses in a given direction were almost entirely accounted for by a linear response to the measured input in the same direction.

Fig. 5 illustrates the seat pan transmissibilities and partial coherences between 1 and 10 Hz for two females and two males (weight range = 53–97 kg) exposed to Signal 2 using the GS seat. The figure shows the transmissibilities between the input and output occurring in the same direction. The seat transmissibilities for exposure to the locomotive signals were not as consistent as those observed for the FLAT exposure. In several instances, multiple peaks were identified between 1 and 10 Hz. The partial coherences were also more variable as shown in Fig. 5 when compared to Fig. 3a for the GS seat pan. Off-axis transmissibilities were observed with values greater than unity, but were associated with low coherences. There were peak transmissibilities for Signal 1 and Signal 2 that were coincident with the peaks observed for the FLAT exposure. Although variable, the partial coherences associated with these peaks tended to be higher than the coherences associated with other peaks. Multiple peaks below 10 Hz were particularly noted in the $Z$-axis transmissibilities for the BS seat. The associated coherences for the seat pan and seat back were quite low (below 0.5). A comparison of the $Z$-axis time histories between the GS and BS seats did reveal clear amplification of the peak response between 2.0 and 4.0 Hz for the BS seat.

### 3.2. Transmission ratio (1–10 Hz)

The transmission ratio, calculated between 1 and 10 Hz where the major responses were observed, provided a tool for comparing the low frequency seat transmission characteristics among the exposures, seat configurations, measurement sites, directions, and posture. Fig. 6 includes the seat pan transmission ratios for each seat configuration in each direction for exposure to the FLAT signal and Signal 2 with the back-on posture. Significant effects of seat

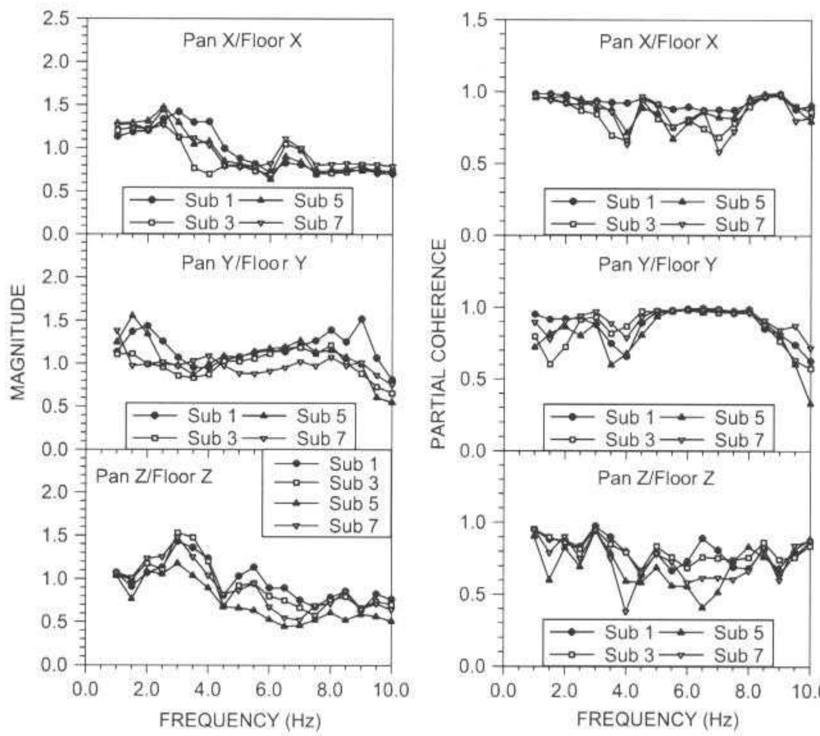


Fig. 5. Seat pan transmissibilities and partial coherences for Signal 2 exposure, GS seat (back-on). (Subject 1 = female, 53.6 kg; subject 3 = female, 94.0 kg, subject 5 = male, 75.6 kg, subject 7 = male, 96.5 kg.)

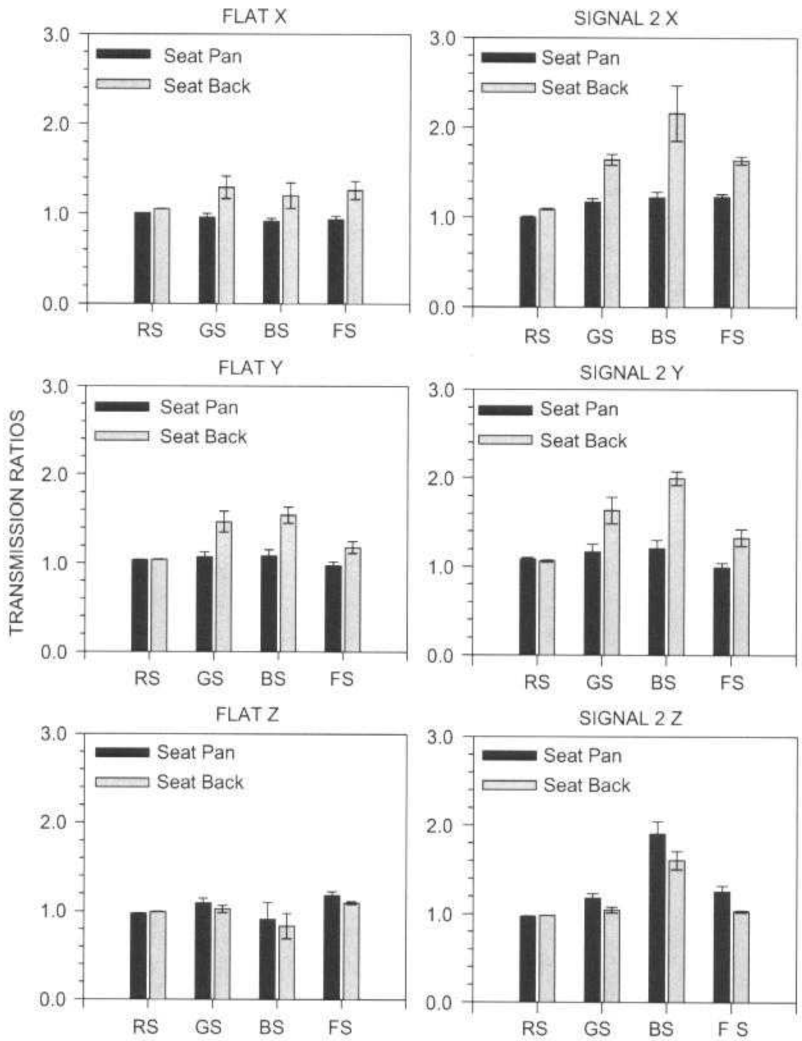


Fig. 6. Mean overall seat pan and seat back transmission ratios $\pm 1$ standard deviation during exposure to the FLAT spectrum and Signal 2.

configuration were found. In the $X$ direction, the GS, BS, and FS seats showed seat pan transmission ratios that were statistically higher as compared to the RS seat during exposures to Signals 1 and 2. The mean transmission ratios were approximately 1.2–1.3 compared to approximately 1.0 for the RS (as expected). In the $Y$ direction, all seats showed significantly higher seat pan transmission ratios as compared to the FS for all exposures, although the differences were not dramatic. In the $Z$ direction, the BS seat showed a significantly lower seat pan transmission ratio as compared to the GS and FS seats during the FLAT exposure. In contrast, in the $Z$ direction, the BS seat showed dramatically higher overall seat pan transmission ratios compared to all other seat configurations during exposures to Signals 1 and 2, with values reaching greater than 1.8. The GS and FS seats showed significantly higher $Z$-axis seat pan transmission ratios when compared to the RS seat, but only for exposure to Signal 2.

Fig. 6 includes the seat back transmission ratios with the back-on posture. As with the seat pan, significant effects of seat configuration were found. In the horizontal directions, the seat back transmission ratios were notably higher with all seats as compared to the RS seat and higher compared to the seat pan regardless of the exposure. In the vertical direction, similar to the seat pan, the BS seat back showed a significantly lower transmission ratio during the FLAT exposure but a significantly higher transmission during exposures to Signals 1 and 2 as compared to the remaining seats.

Although the back-off posture showed overall seat pan transmissions that were statistically higher than the back-on posture, particularly for the FLAT exposure in the horizontal directions, the differences were relatively small. It did appear that the occupant in contact with the seat back dampened the vibration at the seat back, particularly in the $X$ direction.

### 3.3. Health and comfort assessment

The highest weighted seat pan accelerations (calculated between 1 and 10 Hz) occurred in the $Z$ direction for all three locomotive seats. Fig. 7 illustrates these values for exposure to Signal 2. The figure shows that prolonged exposure to Signal 2 using the BS seat will reach the lower boundary of the ISO Health Guidance Caution Zone (Eq. B.1, ISO, 1997) in approximately 1 h and the upper boundary in approximately 4.2 h. The GS seat showed the longest allowable exposure times before reaching the boundaries of the ISO Health Guidance Caution Zone.

The assessment of comfort used both the seat pan point VTV alone (with $k = 1.4$ in the horizontal directions as recommended by ISO 2631-1: 1997 when the seat back is considered to affect comfort but not measured) and the overall VTV (with $k = 1.0$ for the seat pan $X$, $Y$, and $Z$; $k = 0.8$ for seat back $X$; $k = 0.5$ for seat back $Y$; and $k = 0.4$ for seat back $Z$). Fig. 8 illustrates the comfort reactions based on these two calculations. Using the seat pan point VTV, all of the subjects using the GS seat, only one subject using the BS seat, and four subjects using the FS seat would consider the vibration "uncomfortable." Six of the subjects using the BS seat and three of the subjects using the FS seat would consider the vibration "very uncomfortable." When using the combined weighted data for the seat pan and seat back, i.e., the overall VTV, only three subjects using the GS seat would consider the vibration "uncomfortable," while the remaining subjects would consider the vibration "very uncomfortable." All subjects using the BS and FS seats would consider the vibration "very uncomfortable."

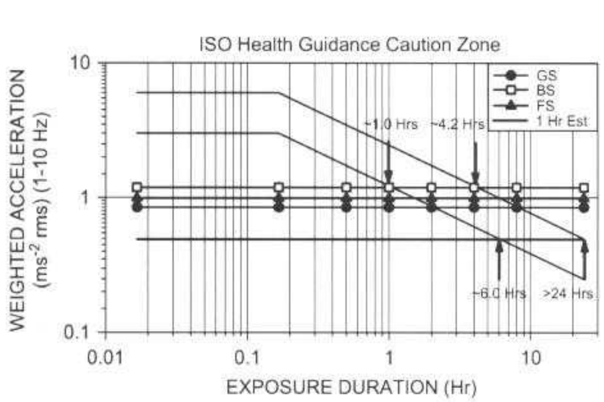


Fig. 7. ISO Health Guidance Caution Zones for locomotive seats based on $Z$-axis weighted seat pan accelerations for Signal 2. (Solid line is estimated weighted $Z$-axis seat pan acceleration for 1-hr field exposure. See Section 4.)

### 3.4. Seat effective amplitude transmissibility (SEAT)

The SEAT was calculated for the frequency range of 1–10 Hz for the three locomotive seats during exposure to Signals 1 and 2. Minimal differences were found between the two exposures. Fig. 9 illustrates the mean SEAT values$\pm 1$ standard deviation calculated between 1 and 10 Hz for each locomotive seat during exposure to Signal 2. Included for comparison are the mean unweighted transmissions calculated between 1 and 10 Hz for Signal 2. The figure shows unweighted and weighted ratios that are similar in the $X$ direction and relatively similar in the $Y$ direction. However, in the $Z$ direction, the unweighted ratio shows that the BS seat amplifies the motion to a greater extent than what the occupant would perceive relative to sitting on the floor (Griffin, 1990). For the locomotive signals, the SEAT values ranged from 1.2 to 1.6 in the $X$ direction (mean $= 1.3 \pm 0.1$), 0.7–1.5 in the $Y$ direction (mean $= 1.0 \pm 0.2$), and 1.0–2.2 in the $Z$ direction (mean $= 1.2 \pm 0.3$), depending on the seat.

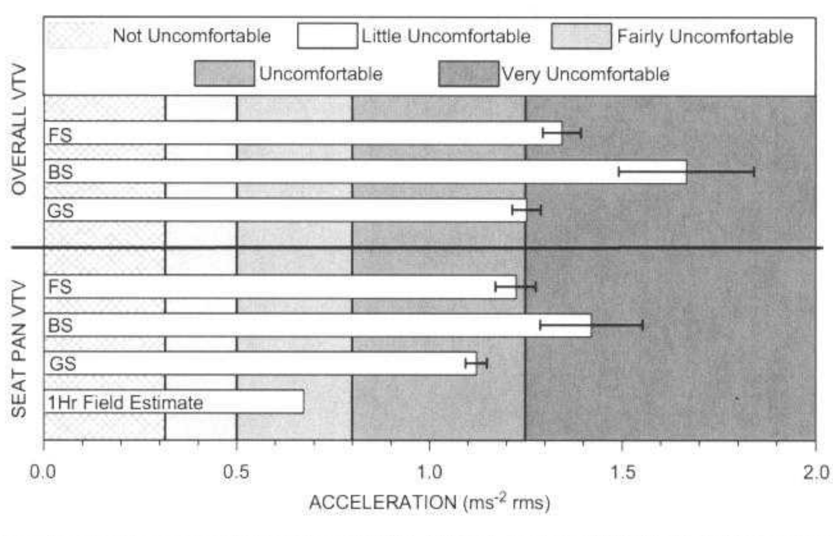


Fig. 8. ISO comfort reactions based on the seat pan VTV and overall VTV. (Estimated seat pan VTV for 1-h field exposure also shown. See Section 4.)

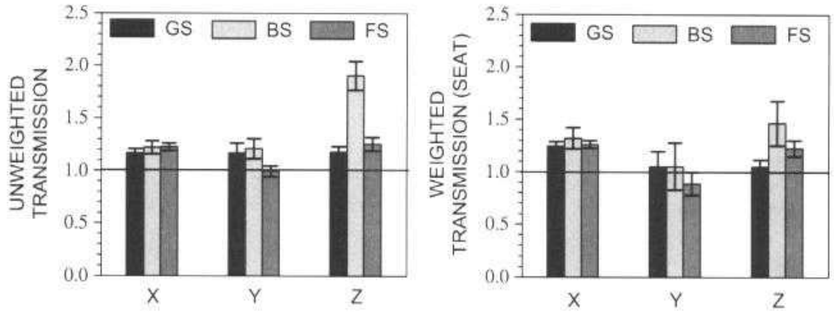


Fig. 9. Mean seat pan transmission ratios and SEAT values ±1 standard deviation for exposures to Signal 2.

## 4. Discussion

The vibration transmission characteristics were determined for selected locomotive suspension and freight seats. The data collected for the FLAT exposure provided the optimum information for estimating the system transfer matrix between the occupant and seat since the acceleration levels were similar at all frequency components. The results showed that, regardless of the seat configuration or posture, the output in any given orthogonal direction at the seat pan and seat back was accounted for by a linear response to the measured input at the floor in the same direction with very minimal cross-axis or other factor effects. This simplifies the estimation of transfer functions for predicting the seat pan and seat back responses from the floor measurements. However, the results for the locomotive exposures did show that other factors contributed to the seat pan and seat back motions in any given direction, i.e., the output at these locations could not be fully accounted for by either a linear response to the input in the same direction or a linear response to an input occurring in another direction. For the operational exposures, the responses at the seat pan and seat back could not be easily predicted using the system transfer matrix.

The transmission ratio provided a simple and realistic metric for evaluating differences in the seat responses due to the type of exposure, seating configuration, measurement site, vibration direction, and posture. For example, the mean vertical responses at the BS seat pan were similar for the two operational exposures (Signals 1 and 2), but were significantly higher as compared to the seat pan responses during the FLAT exposure (Fig. 6). All three locomotive seats showed higher seat back transmissions in the horizontal directions as compared to the RS seat and, similar to the tendencies observed in the transmissibility data (Fig. 6).

Both the transmissibilities and transmission ratios calculated in this study demonstrated the strong influence of coupling between the seat back and human in the horizontal directions, particularly in the fore-and-aft ($X$) direction when using non-rigid seating systems in multi-axis environments. This influence has been observed by others under various test conditions. Recently, Rakheja et al. (2006) exposed subjects to vertical vibration while seated with a back angle of 24° from the vertical. The apparent mass normal to the back rest (fore-and-aft or $X$ direction of the occupant) showed peak values that were at least similar to the apparent mass measured at the seat base in the vertical direction. The peak seat back responses observed in this study with non-rigid seats were most likely influenced by the presence of horizontal vibration, particularly with a relatively small seat back angle of 6°. The frequency location of the peak responses was most likely influenced by the low frequency suspension system. In addition, it is reasonable to assume that a back-on posture would result in dampening of the seat back vibration as compared to vibration of the seat back alone. However, it was reported that the horizontal vibration at the chest was higher with the back-on posture (Smith et al., 2006), emphasizing the human/seat back coupling. It appeared that the occupant was able to stabilize low frequency, upper torso motion when not restricted by movement of the seat back.

The variability observed among the subjects in the peak seat back fore-and-aft ($X$) transmissibility (Figs. 3b and 4b) did not appear to be related to subject weight, although this observation is based on limited data. As suggested in the study by Rakheja et al. (2006), the variability may be related to how well the subject was in contact with the seat back accelerometer pad during the measurements. Subject stature could certainly influence the contact characteristics, depending on the location of the acceleration pad.

In the current study, the high coherences associated with the FLAT exposure suggested minimal rotation of the upper torso. The transmissibility results for exposure to the low frequency locomotive signals indicated that other factors may be contributing to the responses that could include upper torso rotation. However, the multiple low frequency peaks and particularly low partial coherences observed at the seat pan and seat back in the vertical direction with the BS seat did suggest the influence of periodic contact with the rubber bumpers or end-stops. As mentioned previously, this did not result in substantial

shock-like behavior but may have contributed to the multiple low frequency peaks (<10 Hz) observed in the data and the higher transmission ratios.

The SEAT values strongly suggested that the measured floor data could underestimate the health risk and discomfort of the operational exposures, particularly in the $X$ and $Z$ directions (SEAT > 1.0). Although Signal 1 and Signal 2 were extracted from data collected during travel on different legs of a route, the associated frequency spectra and SEAT values were similar. The SEAT does provide a simple method for calculating the weighted seat pan acceleration in each direction, the minimum requirement for assessing health risk and discomfort in accordance with ISO 2631-1: 1997. This does require the selection of SEAT values in the $X$, $Y$, and $Z$ directions that represent the operational conditions. The mean SEAT values for the locomotive signals were 1.3 in the $X$ direction, 1.0 in the $Y$ direction, and 1.2 in the $Z$ direction. Given the higher SEAT value for the BS seat in the $Z$ direction (mean = 1.6 (Signal 1) and 1.5 (Signal 2)), it may be more appropriate to use a SEAT value of 1.3 in the $Z$ direction to cover all seating configurations. These selected SEAT values were multiplied by the weighted floor accelerations obtained from the 1-h operational acceleration from which Signal 2 was extracted to give the weighted accelerations in each direction. Using $k = 1.4$ for the horizontal directions, the highest weighted acceleration was $0.494\,\mathrm{m\,s^{-2}}$ rms and occurred in the $Z$ direction. Assuming that the 1-h exposure is representative of longer duration exposures, the lower boundary of the ISO Health Guidance Caution Zones would be reached in 6 h as compared to 1 h for Signal 2 as shown in Fig. 7. It is noted that Signal 2 contained the highest accelerations observed in the 1-h sequence. For comfort, the seat pan point VTV using $k = 1.4$ in the horizontal directions was $0.673\,\mathrm{m\,s^{-2}}$ rms. This corresponds to a comfort reaction of "fairly uncomfortable." The seat pan point VTV was used in the assessment since no estimation of the weighted seat back acceleration could be made from the floor measurements.

Caution should be taken in assessing the health risk and discomfort of the low frequency exposures encountered by the locomotive engineers using the SEAT values to estimate the weighted seat pan accelerations. Although the highest weighted acceleration occurred in the $Z$ direction ($0.494\,\mathrm{m\,s^{-2}}$ rms), substantial vibration also occurred in the $X$ direction ($0.441\,\mathrm{m\,s^{-2}}$ rms). The $X$-axis exposure is not accounted for in determining the amount of operating time that can pass before reaching the lower boundary of the ISO Health Guidance Caution Zones. ISO 2631-1: 1997 does suggest that the vector sum could be used to assess the health risk when vibration in two or more directions is similar. The vector sum of the weighted acceleration in the $X$, $Y$, and $Z$ directions (including the appropriate $k$ values) is $0.673\,\mathrm{m\,s^{-2}}$ rms (identical to the seat pan point VTV for assessing comfort). The lower boundary would be reached in 3.3 h. The upper boundary would be reached in 13 h. In addition, any contribution from the seat back is not included in the health assessment. Even the 3.3 h may be an underestimate of the time required to reach the condition where caution should be taken with respect to health risk. With respect to the comfort reactions, the SEAT provides for estimating only the weighted seat pan accelerations and not the weighted seat back accelerations. Even though the 1.4 multiplying factor is used as recommended by ISO 2631-1: 1997, Fig. 8 shows that using the seat pan VTV alone may underestimate the discomfort. For low frequency exposures where the seat back transmits substantial vibration to the occupant, an effective amplitude transmissibility between the seat back and floor may provide a more accurate assessment.

There have been a few studies conducted in the US for assessing the vibration exposure in both freight and passenger trains. In a study conducted by Fries et al. (1993) on eight freight locomotives, the highest vibration occurred in the vertical direction, as shown in the examples used in the current study. In a study by Johanning et al. (2002), locomotive vibration was assessed in 22 US locomotives. Four of the seating systems appeared to be similar to those used in the current study, although the locomotives may have been different (total of six tests). Their results did show that the highest weighted seat pan accelerations occurred in the vertical ($Z$) direction. The weighted values in the $Z$ direction ranged from 0.24 to $0.50\,\mathrm{m\,s^{-2}}$ rms compared to $0.494\,\mathrm{m\,s^{-2}}$ rms estimated for the 1-h field exposure using the SEAT values calculated in this study. The vector sum of the weighted accelerations (using $k_x = k_y = 1.4$) ranged from 0.36 to $0.63\,\mathrm{m\,s^{-2}}$ rms for these seats. The vector sum estimated for the 1-h field exposure in this study was higher at $0.673\,\mathrm{m\,s^{-2}}$ rms. Johanning et al. (2002) also calculated the SEAT value as described in the current study. For the four seating systems, the SEAT value ranged from 1.0 to 1.7 in the fore-and-aft ($X$) direction, from 0.8 to 1.2 in the lateral ($Y$) direction, and from 0.8 to 1.6 in the vertical ($Z$) direction. Only one of these seating systems showed a SEAT value of 1.6 in the vertical ($Z$) direction; the remaining five seats were at or below 1.1. More recently, Johanning et al. (2006) assembled acceleration data from 51 revenue-service locomotives. The mean weighted acceleration in the vertical ($Z$) direction was only $0.29 \pm 0.08\,\mathrm{m\,s^{-2}}$ rms but the maximum was observed at $0.50\,\mathrm{m\,s^{-2}}$ rms. The mean vector sum of the weighted seat pan accelerations was $0.48 \pm 0.21\,\mathrm{m\,s^{-2}}$ rms with the maximum value at $1.44\,\mathrm{m\,s^{-2}}$ rms. The highest SEAT value occurred in the fore-and-aft ($X$) direction, with a mean of 1.39 and maximum of 2.19. The mean SEAT was 1.21 in the lateral ($Y$) direction and 0.97 in the vertical ($Z$) direction. The distribution of the accelerations and SEAT values relative to the type of seat was unknown. The SEAT value selected to predict the seat pan accelerations in this study was similar to the median values shown in the fore-and-aft ($X$) direction for all 22 locomotives in the 2002 study and lower as compared to the 2006 study (SEAT = 1.3), lower than

both the median value in the lateral ($Y$) direction in the 2002 study and the mean value in the lateral ($Y$) direction in the 2006 study (SEAT = 1.0 compared to 1.2), and similar to both the median value in the vertical ($Z$) direction in the 2002 study and the mean value in the vertical ($Z$) direction in the 2006 study (SEAT = 1.0). However, as indicated previously, a SEAT value of 1.3 was selected for the vertical ($Z$) direction, given the higher transmission characteristics associated with the BS seat.

The results of this study do suggest that using passive suspension seats in vibration environments where the major frequency components coincide with the resonance characteristics of the seating system may not be the best approach to mitigating large occupant motions. In addition, where there is substantial vibration in the $X$- or $Y$-axis of the body, horizontal suspension systems may be useful additions. Recent studies by Blüthner et al. (2006), Fleury and Mistrot (2006), Schust et al. (2006), and Stein et al. (2006), address modeling and optimization of horizontal suspensions.

## 5. Conclusions

For the low frequency exposures used in this study, the multi-axis seat pan vibration cannot be easily predicted from the system transfer matrix without considering the effects of off-axis coupling and other factors or noise.

The seat pan and seat back transmission ratios provided a useful tool for evaluating the effects of the seating system, measurement site, vibration direction, and posture on the occupant/seat transmission characteristics.

The use of SEAT values based on exposures with similar frequency and magnitude characteristics and where similar seating systems are used may be advantageous for targeting potentially harmful vibration from monitored floor data. However, when substantial low frequency multi-axis vibration is present, the vibration transmission at the seat back should be considered in the assessment. Whenever possible, every attempt should be made to measure the vibration at the interfaces where the occupant comes in contact with the seat.

Low frequency vibration can be mitigated by insuring that the suspension seat is in optimum operating condition (GS vs. BS).

Although this study suggested that the vibration experienced by the locomotive engineers was less than ideal, the equipment conditions at the time of the field data collection may have changed. If the frequency distribution and magnitude were sufficiently altered in any of the directions, the SEAT values estimated in this study may be inappropriate. This can be determined by comparing the monitored floor data.

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## References

Bendat, J.S., Piersol, A.G., 1993. Engineering Applications of Correlation and Spectral Analysis. Wiley, New York.

Blüthner, R., Hinz, B., Menzel, G., Schust, M., Seidel, H., 2006. On the significance of body mass and vibration magnitude for acceleration transmission of vibration through seats with horizontal suspensions. Journal of Sound and Vibration 298 (3), 627–637.

Corbridge, C., 1987. Vibration in vehicles: its effect on comfort. Ph.D. Thesis, University of Southampton, Southampton, England.

Couvreur, C., 1997. Internet MATLAB Computer File. Faculte Polytechnique de Mons, Belgium.

Fleury, G., Mistrot, P., 2006. Numerical assessment of fore-and-aft suspension performance to reduce whole-body vibration of wheel loader drivers. Journal of Sound and Vibration 298 (3), 672–687.

Fries, R.H., Cooperrider, N.K., Larson, R.E., 1993. Locomotive and road vehicle ride quality assessments. Rail Transportation 6, 219–227.

Griffin, M.J., 1990. Handbook of Human Vibration. Academic Press, London.

International Organization for Standardization (ISO), 1990. Vibration and shock—vocabulary. ISO 2041: 1990.

International Organization for Standardization (ISO), 1992. Mechanical vibration—laboratory method for evaluating vehicle seat vibration—Part 1: Basic requirements. ISO 10326-1: 1992.

International Organization for Standardization (ISO), 1997. Mechanical vibration and shock—evaluation of human exposure to whole-body vibration—Part 1: General requirements. ISO 2631-1:1997.

Johanning, E., Fischer, S., Christ, E., Göres, B., Landsbergis, P., 2002. Whole-body vibration exposure study in US railroad locomotives—an ergonomic risk assessment. AIHA Journal 63, 439–446.

Johanning, E., Landsbergis, P., Fischer, S., Christ, E., Gores, B., Luhrman, R., 2006. Whole-body vibration and ergonomic study of US railroad locomotives. Journal of Sound and Vibration 298 (3), 594–600.

Naidu, P.S., 1996. Modern Spectrum Analysis of Time Series. CRC Press, Boca Raton.

Newland, D.E., 1984. An Introduction to Random Vibrations and Spectral Analysis. Longman Inc., New York.

Rakheja, S., Stiharu, I., Zhang, H., Boileau, P.É., 2006. Seated occupant interactions with seat backrest and pan, and biodynamic responses under vertical vibration. Journal of Sound and Vibration 298 (3), 651–671.

Schust, M., Blüthner, R., Seidel, H., 2006. Examination of perceptions (intensity, seat comfort, effort) and reaction times (brake and accelerator) during low-frequency vibration in x- or y-direction and biaxial (xy-) vibration of driver seats with activated and deactivated suspension. Journal of Sound and Vibration 298 (3), 606–626.

Smith, S.D., 1997. Cushions and suspensions: predicting their effects on the transmission of vibration in the human. Heavy Vehicle Systems, International Journal of Vehicle Design 4 (2–4), 296–316.

Smith, S.D., Smith, J.A., Newman, R.J., 2006. Vibration transmissibility characteristics of occupied suspension seats. US Air Force Research Laboratory, Dayton, OH, Human Effectiveness Directorate, Wright-Patterson AFB, AFRL-HE-WP-TR-2006-0133.

Stein, G.J., Múčka, P., Chmúrny, R., 2006. Preliminary results on x-direction apparent mass model of human body sitting in a cushioned, suspended seat. Journal of Sound and Vibration 298 (3), 688–703.

Welch, P.D., 1967. The use of Fast Fourier Transform for the estimation of power spectra: a method based on time averaging over short, modified periodograms. IEEE Transactions of Audio Electroacoustics AU-15, 70-3.